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Research Paper

Figure of merit for optimization of nanofluid flow in circular microchannel by adapting nanoparticle migration

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HIGHLIGHTS

- Thermally fully developed flow of nanofluid in circular microchannels at constant wall temperature.
- Effect of nanoparticle migration on fluid flow and heat transfer characteristics.
- Thermal performance gets its peak around $N_{BT} = 0.4$.
- Anomalous heat transfer rate occurs for $N_{BT} = 1$.
- Optimum value of N_{BT} for the case of CWT is greater than that of CHF.

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ABSTRACT

In this paper, the laminar fully developed flow of alumina/water nanofluid inside circular microchannels subjected to a constant wall temperature (CWT) is theoretically investigated. The effect of nanoparticles migration originating from thermophoretic diffusion (temperature-gradient driven force) and Brownian diffusion (concentration-gradient driven force) on the thermophysical characteristics of nanofluids has been considered. A Navier's slip condition is considered at the wall to model the non-equilibrium region at the fluid-solid interface. In order to assume a hydrodynamically and thermally fully developed flow, the governing equations are reduced to a system of ordinary differential equation and solved using the appropriate reciprocal algorithm. The effects of pertinent parameters including the ratio of Brownian motion to thermophoresis (N_{BT}), slip parameter (λ) and bulk mean nanoparticle volume fraction (ϕ_B) on the flow and thermal fields are investigated. In addition, the results are compared with the case of constant heat flux (CHF) at the wall. The figure of merit (*FoM*) is used to measure the thermal performance of equipment and finding the optimum thermal condition. It is shown that the anomalous heat transfer enhancement depends on the thermal boundary condition as well as the nanoparticles diameter. Furthermore, the optimum value of N_{BT} for the case of constant wall temperature (approximately 1) is found to be greater than that of the constant wall heat flux (approximately 0.5). Thus, it can be concluded that the optimum diameter of nanoparticles for the case of constant wall temperature should be smaller than that of constant wall heat flux.

1. Introduction

Nanofluids (colloidal suspensions of nanoparticles in base fluid) possess novel properties including the greater specific surface area, more stable colloidal suspension, lower pumping power for a specific heat transfer rate, reduced clogging compared to regular cooling colloids, and the ability to adjust the thermophysical properties of suspensions by changing the nanoparticle materials and physical conditions, volume fraction of particles, particles size, and their shape. These novel characteristics make nanofluids suitable for several industrial applications such as pharmaceutical processes (drug delivery), surfactant and coating, cooling in heat exchangers, fuel cells, hybrid-powered engines, solar PV, and microelectromechanical systems (MEMs).

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Nomenclature

c_p	specific heat capacity (m^2/s^2 K)
dp	nanoparticle diameter (m)
Dh	hydraulic diameter, $D_h = 2R_o$ (m)
D_B	$= \frac{k_{BO}T}{3\pi\mu_{bf}d_p}$, Brownian diffusion coefficient (m^2/s)
D_T	$= 0.26\frac{k_{bf}}{2k_{bf}+k_p}\frac{\mu_{bf}}{\rho_{bf}}\phi$, thermophoresis diffusion coefficient (m^2/s)
FoM	figure of merit
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
k_{BO}	Boltzmann constant ($= 1.3806488 \times 10^{-23}$ m^2 kg/s^2 K)
N	slip velocity factor
Nu	Nusselt number
N_{BT}	ratio of the Brownian to thermophoretic diffusivities
P	pressure (Pa)
q_w	surface heat flux (W/m^2)
T	temperature (K)
u	axial velocity (m/s)
x, r	coordinate system

Greek symbols

ϕ	nanoparticle volume fraction
γ	ratio of wall and fluid temperature difference to absolute temperature
η	transverse direction
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
λ	slip parameter
θ	internal angle inside cross-section of microtube

Subscripts

B	bulk mean
bf	base fluid
p	nanoparticle
w	condition at the wall

Superscripts

$*$	dimensionless variable

1.1. Theoretical modeling of nanofluids

Several theoretical models have been introduced so far to calculate the behavior of nanofluids on convective heat transfer. The proposed models, however, depend on certain inputs from experimental observations. Each model acquiring the best conformity to the experimental observations is construed as an accurate model by those researchers. In the literature, the heat transfer coefficients were determined by modeling the nanofluid as either single or two-phase flow. The most important findings from the experiments are: (a) an abnormal increase in the thermal conductivity of nanofluids with respect to the regular fluid [1]; (b) an abnormal increase in the viscosity of nanofluids relative to the regular fluid [2,3]; and (c) an abnormal single-phase heat transfer coefficient of nanofluids with respect to the regular fluid [4]. In 2006, Buongiorno [5] proved that the single-phase model as well as the dispersion models cannot accurately follow the experimental observations. Accordingly, he proposed a two-component (solid and fluid) four-equation (continuity, momentum, energy, and nanoparticle flux) heterogeneous equilibrium model to illuminate the experimental findings. In the Buongiorno model, nanoparticle fluxes are considered in accordance with the two important slip mechanisms: Brownian diffusion (or Brownian motion) and thermophoresis (or thermophoretic diffusion). Next, after taking Buongiorno's model into consideration in different geometries, several investigations are performed on the convective heat transfer in nanofluids; for instance, Sheremet et al. [6], Yadav et al. [7], Sheikholeslami and Ellahi [8], Garoosi et al. [9], and Nield and Kuznetsov [10]. Theoretical investigation on the effect of nanofluids has been systematically reported and well documented, which can be found in the open literature [11–15]. An excellent review paper on the application of nanofluids in microchannels is conducted by Salman et al. [16].

1.2. Nanoparticle migration effects

In 2013, Yang et al. [17,18] modified the Buongiorno's model to consider the impact of nanoparticle distribution on the thermal conductivity and viscosity of nanofluids. In fact, the proposed modified model does not ignore the dependency of thermophysical properties of nanofluids to the nanoparticles concentration. Their results indicated that the non-uniformity of the thermophysical properties is the reason for the anomalous heat transfer enhancement. Malvandi and Ganji [19], then, used the modified model to examine the mutual impacts of buoyancy and nanoparticle migration on the mixed convection of nanofluids in vertical annuli. Subsequently, Malvandi and Ganji [20] investigated the impacts of the nanoparticle migration as well as asymmetric heating at the walls on the forced convective heat transfer of magnetohydrodynamic alumina/water nanofluid in microchannels. Hedayati and Domairry [21] investigated the effects of the nanoparticle migration on titania/water nanofluids in horizontal and vertical channels. The popularity of modeling the nanoparticle migration can be gauged from the numerous published works of literature such as [22–27].

1.3. Motivation and novelty

From the previous explanations, the utilization of the modified Buongiorno model has been limited to a special thermal boundary condition that provides the constant heat flux at the boundaries. Recently, Malvandi and Ganji [20] demonstrated that because of thermophoresis, asymmetrically heated walls are able to control the fluid flow and heat transfer characteristics of nanofluids. In addition, the amount of enhancement in the heat transfer rate can be controlled by adjusting the heat flux at the boundaries. These outcomes pointed out that thermal boundary conditions are a key factor in the fluid flow and heat transfer characteristics of nanofluids. Accordingly, in this paper, a prescribed wall temperature as a widespread thermal boundary condition is imposed on the wall, which is an important development for the modified Buongiorno model [28,29]. The fully developed governing equations of the modified Buongiorno model are obtained and the results for the pressure drop and the heat transfer enhancement are presented versus varying pertinent parameters. Because of low dimensional structures in microchannels, a linear slip condition is considered at the surfaces, which appropriately represents the non-equilibrium region near the fluid/solid interface. To study the thermal performance, the figure of merit (FoM) is calculated to signify it. The impacts of the thermal boundary condition, nanoparticle migration, as well as the slip velocity on thermal performance are of our particular interests.